Preliminary test results of an axial flux toroidal stator wind power generator

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ABSTRACT

The use of wind power to produce energy has increased rapidly in recent years. Simultaneously a need for a more efficient design has arisen. Today a common drive consists of a constant speed turbine, a gearbox and an asynchronous generator connected directly to the grid. In order to increase the energy capture a variable speed turbine connected directly to a special type of generator may be used. The generator is connected to the grid via a frequency converter. An axial flux toroidal stator permanent magnet synchronous generator might be suitable for this purpose. Such a generator with a nominal power of 100 kW has been designed and built and the test results are presented here.

Keywords: Permanent magnet, toroidal, wind power generator.

1 INTRODUCTION

In recent years the wind power industry has grown considerably. By the end of 1999 a capacity of 13 000 MW was installed. In the last three years the installed capacity has been doubled and it is commonly believed that in the coming three years it will double again. This growth has given rise to attempts and investments to find more efficient designs. Three basic development trends may be seen to prevail, including use of variable speed operation, permanent magnet excitation and direct driven generator.

It has been estimated [3] that 10-15% increase in the wind energy capture can be attained by using variable speed operation instead of constant speed operation. Variable speed operation requires a frequency converter between the generator and the grid. Use of variable speed and frequency converter results in several benefits in the generator design. Generator dimensions may be designed for maximum efficiency, since they are not affected by grid frequency. Furthermore, the generator output does not have to be in three phase form and no additional damping is needed in the entire drive train.

Permanent magnet excitation leads to a higher efficiency, since no external magnetization is needed. An asynchronous generator used commonly in wind power applications needs reactive magnetization power, which is a problem especially in remote areas. Availability of modern high energy density magnet materials based on rare earth metals has made it possible to design special topologies such as ones containing toothless stator with air gap windings. The price of these materials has been decreasing, which will promote their use in the near future.

Using a direct driven generator eliminates the need of a gearbox, which reduces weight and need for maintenance and also increases reliability and efficiency. On the other hand, direct drive sets some special requirements to the generator. The number of poles must be very large since the rotational speed of turbine is very low, on the order of 10 to 30 rpm in modern mills. A large number of poles is easily achieved using permanent magnets (PM) and thus wind power PM generators have been widely studied. An axial flux toroidal stator PM generator has been one of the many candidates and has been studied in [1-5], similar special machines also in [6-11]. A prototype generator with a nominal power of 100 kW has been designed and built in Tampere University of Technology. Preliminary test results are presented in this paper.

2 MACHINE LAYOUT

The prototype generator has a simple construction, which is outlined in Figs. 1 and 2. The cross section of the generator is presented in Fig. 1 and the active parts in peripheral plane are presented in Fig. 2. The stator is a toroid wound of mild iron tape to avoid eddy currents. The stator carries rectangular coils which form a three phase air gap winding. Rotor discs made of massive mild steel reside on both sides of the stator. Permanent

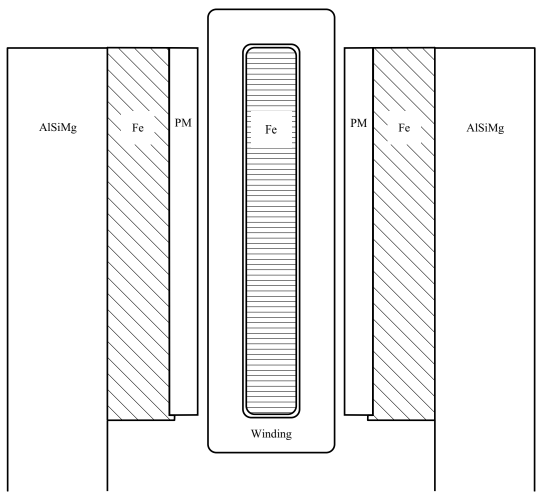

Fig. 1. Cross section of axial flux disc type generator.

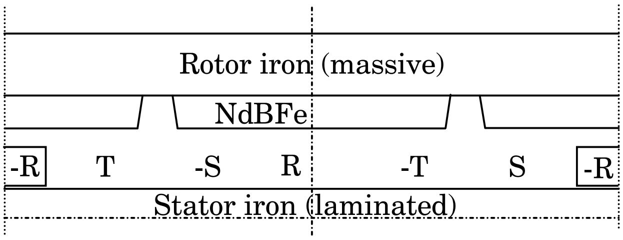

Fig. 2. Active parts in peripheral plane.

magnets are attached to the rotor rings. The PMs are made of neodymium-boron-iron (NdBFe), which has a very large energy density. Thus NdBFe magnets are capable of producing a large air gap flux density even in machines with air gap winding.

A large number of poles can be achieved with PMs. This type of machine layout leads to several other advantages. The construction is simple containing no teeth and the stator core can be wound directly from tape. The PMs are rectangular, while in the traditional radial-flux machines they would be arc shaped. Due to the PMs there is no need for the external magnetization, which is important especially in stand-alone wind power applications and also in remote areas where the grid cannot easily supply the reactive power required to magnetize the induction generator. Due to the very short end windings the resistance and consequently I^2R-losses are small. Iron losses are also small due to the laminated stator core and the absence of the armature reaction. The winding being in the airgap field causes eddy currents in the conductors but by proper dimensioning of the winding the losses can be reduced to an acceptable level. Low losses and the absence of external magnetization lead to high efficiency over wide range of speed and power. Slotless winding provides a very large magnetic airgap between the stator and the rotor iron cores causing the self and mutual inductances to be extremely small. In addition, the obvious absence of the slot leakage flux further decreases the inductances. The absence of teeth also eliminates the cogging torque and thus reduces noise.

Prototype generator dimensions are presented in Table 1. The dimensions have been determined by optimization aiming at the minimization of total costs, i.e. the sum of the investment and the energy loss costs over the lifetime. Investment costs consist of active part material costs and structural costs. Active part material costs are evaluated with the aid of magnetic circuit laws including the empirical correction factors based on experiments from 10 kW model generator described in [1] and [2]. Structural costs depend on outer diameter and length as described in [5]. Energy loss costs are calculated by weighting the loss power as a function of wind speed with the Weibull wind speed probability function and integrating over the entire operational wind speed range. The lifetime of the generator is assumed to be 20 years. A detailed presentation of the optimization is given in [1] and [4]. There are six separate three phase systems in the generator. This type of winding connection has been chosen in order to keep the wire diameter small. A large wire diameter in air gap winding leads to excessive eddy current losses in the winding.

Table 1. Prototype generator parameters

Pole pair number	45
Number of phases	6x3
Outer radius (m)	1.2
Air gap flux density (T)	0.33
Active part length (m)	0.11
Number of turns per coil	30
Winding thickness (mm)	10.0
Wire diameter (mm)	2.5
Wire cross sectional area (mm^2)	4.9
Core thickness (mm)	15.0
Magnet thickness (mm)	8.5
Active part mass (kg)	635
Total mass (kg)	1900

3 TEST RESULTS

Throughout the tests the prototype generator shaft is rotated with an asynchronous motor (250 kW, 1000 rpm) fed by ACS 600 voltage source frequency converter. The generator is operated at fixed speed and load.

3.1 No load tests

Phase resistance of each of the 18 (6x3) phases was measured using four-point measurement. The result at the temperature of 22°C is 0.48 Ω for each phase. The maximum allowed operating temperature for the winding is 120°C [1]. The phase resistance at this temperature is 0.66 Ω [1]. The calculated value of phase resistance is 0.62 Ω at 120°C. Similarly, the self inductance of one phase was measured using step change method giving the result of 13 mH per phase.

In no load tests all the voltage measurements are made using power meter built at Tampere University of Technology. The meter is based on space vector measurement and consequently the shape of the voltage or current curve does not cause any inaccuracies as root-mean-square values are calculated. In three phase measurement the error is ±0.1% and in one phase measurement ±1%. All flux density measurements were made using transverse flux Hall probe connected to Hall Magnetometer 5200 manufactured by Oxford Instruments Ltd. The error is ±0.3% of the full scale of 2 T used here.

The no load phase voltage of each of the 18 phases was measured at the rotational speed of 12 rpm. Theoretically, the phase voltages should be identical except for the phase difference. The results are presented in Fig 3. Per unit values are used and the base voltage is the mean phase voltage of all the phases. There are a number of possible reasons leading to the phase voltage differences observed in Fig. 3. First, there are reasons caused by material defects. The remanent flux density of the magnets may vary and thus the air gap flux density distribution over the pole is not constant. Furthermore, magnetic properties of both rotor and stator iron rings may not be constant along the periphery of the rings, which also leads to different flux density distributions. Second, there are reasons related to manufacturing process. The positioning of the individual coils may be inaccurate i.e. the electrical angle between the coils may not be constant. This does not affect to the voltage waveform but causes a change in the phase angle thus creating a potential difference between phases. Thus extreme care should be taken while mounting the coils to avoid

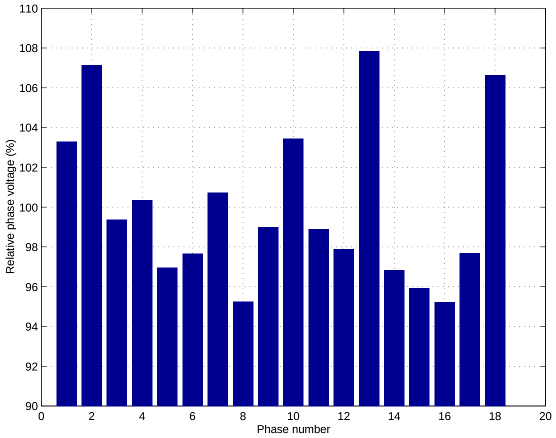

Fig. 3. Phase voltages of prototype generator at no load.

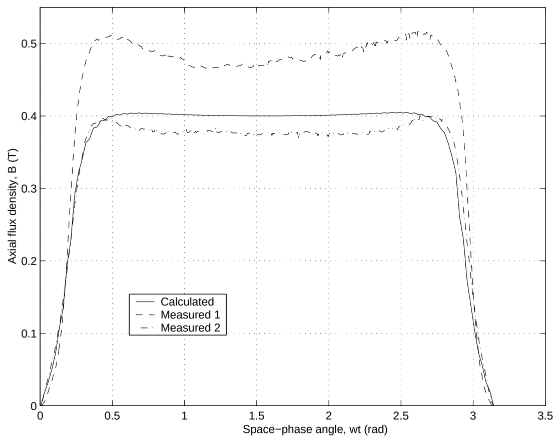

Fig. 4. Axial flux density in air gap.

any misplacement. Also the air gap length is not constant, mainly due to the fact that the rotor iron ring is not straight. The rotor iron ring is supported by twelve rotor spokes. The attractive force between rotor and stator is strong enough to bend the rotor ring towards the stator between the spokes. In future applications the rotor iron should be made thicker than would be magnetically necessary.

In prototype generator all six separate three phase systems are connected parallel so that a regular three phase system is formed. This leads to closed circuits in the generator winding. The difference in phase voltages then causes circular currents in the winding even at no load conditions. The rms value of the circular current is 1.33 A or about 5% of the nominal current. Obviously at nominal rotational speed the circular current is three times as large, which leads to high unnecessary copper losses. Circular currents can be minimized by improving the generator support structure and manufacturing process. Furthermore, they can be totally eliminated by using a separate diode bridge for each of the six three phase systems, which also improves the utilization factor of the generator, since in the case of fault one three phase systems can be disconnected while the others continue to operate normally.

The axial flux density in the air gap was measured by a transverse flux Hall probe placed in the middle of the airgap. The rotational speed of the generator was very small, 3 rpm, in order to avoid the effect of circular currents on the airgap flux density. The measurements were performed on both sides of the stator. The results are presented in Fig. 4. The graph computed with Finite Element Method (2-dimensional model) is also included. Measured graphs 1 and 2 refer to the stator sides. Fig. 4. clearly shows that the airgaps on the stator sides are of a different length. This is mainly due to the labile nature of magnetic circuits. A slightest clearance in bearings allows to rotor to shift from the centered position. Simultaneously a strong force driving the rotor further to the direction of the initial movement is applied to the rotor. Consequently the rotor is not in the centered position. The amount of deviation is dictated by the clearance in the bearings. The rotor can be held in centered position by using the type of bearings having very small or no clearance. Alternatively, additional support bearings at the outer radius of the rotor structure may be used. The difference in airgap lengths has little effect on the coil voltages induced, since the decrease of flux density on the one side of the stator is compensated by increase on the other. Furthermore, the total flux in the stator core remains constant and no excessive saturation should occur. The stray flux should behave similarly, i.e. the increase on one side is compensated by decrease on the other. Consequently, it is the mean value of the two measured graphs that is to be compared to the calculated graph. The mean value of measured axial flux density is slightly higher than calculations predict. This is due to the reasons explained above.

Phase voltage can be calculated using the axial flux density computations performed with FEM and is given by [1]

$$\hat{e} = 2N_c N_t B_{st} l_{act} \omega_m r_m, \quad (1)$$

where N_c is the number of coils per phase, N_t is the number of turns per coil, B_{st} is the axial flux density on stator surface, l_{act} is the radial length of the stator core, ω_m is the mechanical angular frequency and r_m is the mean radius of the stator core. Rotational speed used in Eq. (1) is 35 rpm corresponding to the speed used in no load voltage measurement. The flux density B_{st} given by FEM is presented in Fig. 5. The phase voltage can be calculated using the flux density distribution on the stator surface, since the flux passing through stator coil is equal to the flux entering the stator, which is directly proportional to the flux density on the stator surface. The calculated and measured phase voltages are presented in Fig. 6. showing a nice agreement between them. The measured value is slightly higher, which corresponds well to the fact that also the measured air gap flux density was higher than the calculated air gap flux density.

3.2 Load tests with purely resistive load

During the load tests the generator is connected directly to a water cooled purely resistive three phase load in delta connection. The measurements were made using Norma D6000 three phase power meter and two channel measuring unit based on analog technology. This way the effective and reactive power components were measured at the same time with voltage and current waveforms and rms values.

The effect of armature reaction can be seen in Fig. 7, where

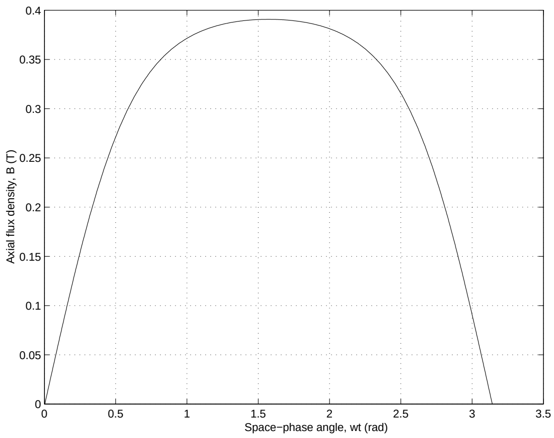

Fig. 5. Axial flux density on stator surface.

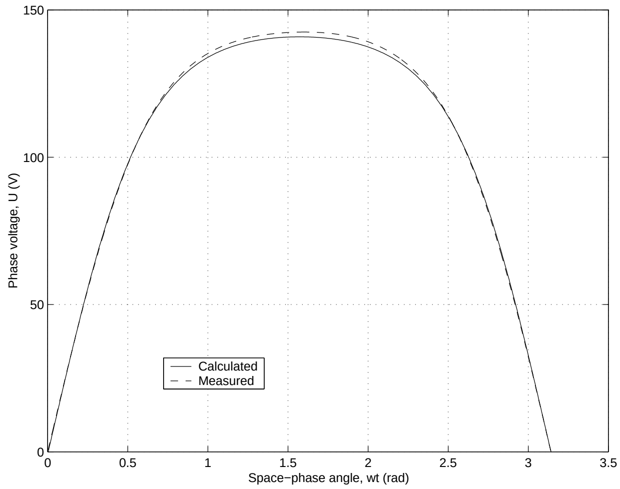

Fig. 6. Phase voltage at no load.

both calculated and measured phase voltage is presented. The calculated voltage curve has been obtained using Eq.(1) and the measured axial flux density. The measurement was made at the rotational speed of 20 rpm and with the phase current of 20 A. The flux induced by the coil currents weakens the flux created by the magnet on one half of the pole and strengthens it on the other half.

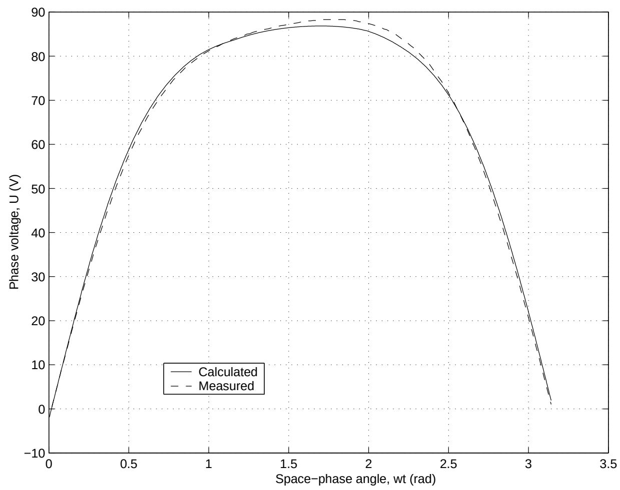

Fig. 7. The effect of armature reaction.

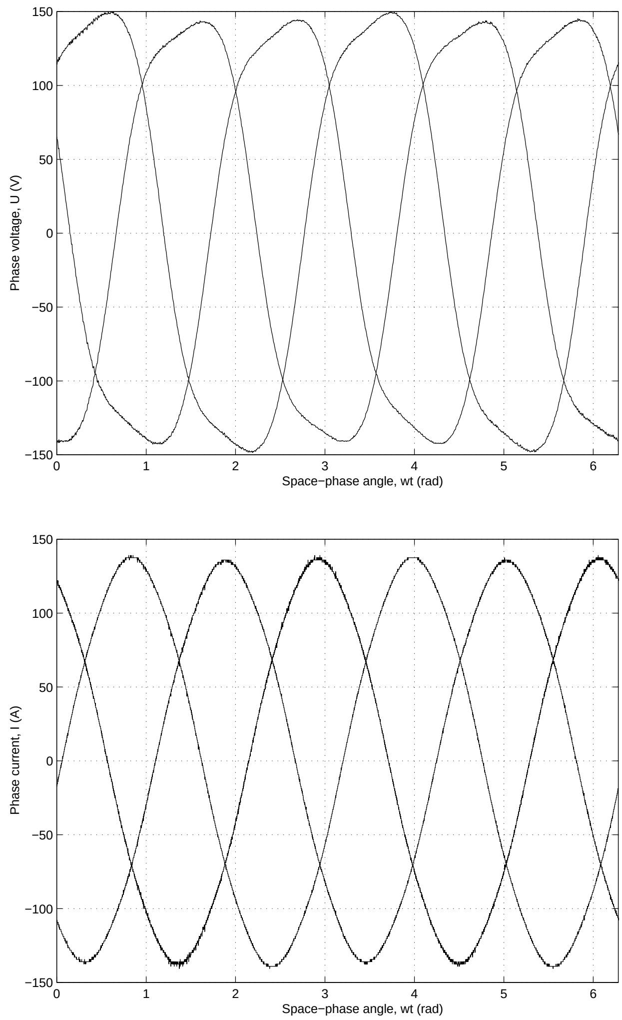

Fig. 8. Phase voltages and currents at 35 rpm. P = 32.5 kW.

Generator phase voltages and currents at the rotational speed of 35 rpm and with the load of 32.5 kW are presented in Fig. 8. The phase voltages are not quite symmetrical due to the reasons explained in connection with Fig. 3. Also the circular currents cause unsymmetry in phase voltages. The effect of armature reaction can also be clearly seen. The unsymmetrical phase voltages cause unsymmetry in phase currents, too.

3.3 Load tests with diode bridge and resistive load

In this test a three phase voltage of the generator was rectified with a diode bridge and the output of the bridge was connected to a 2 Ω resistive load via a 2 mH coil. The measuring device used was the same as in the preceding load tests. The diode bridge was built especially for this purpose and will be used in future tests with the inverter to feed the generator output to the grid. The waveforms of both phase voltage and current are presented in Fig. 9. The effect of commutation is clearly visible in voltage waveform. The corresponding power fed by the generator is presented in Fig. 10. The fluctuation in the power is due to the unsymmetrical phase voltages. The unsymmetry also causes fluctuations in the rectified voltage, since the time between commutations is no longer constant. Consequently also the DC power fluctuates.

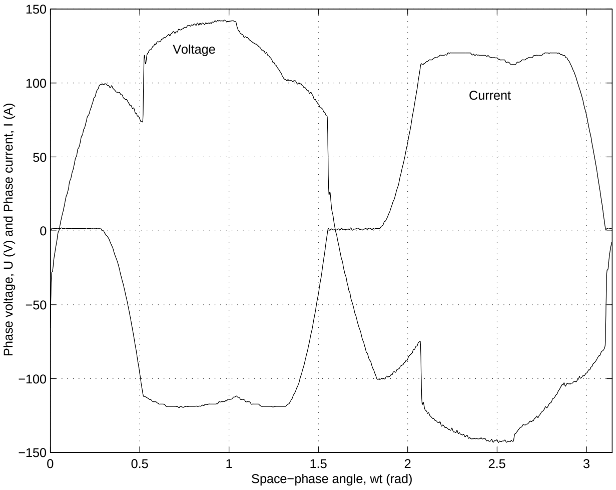

Fig. 9. Phase voltage and phase current waveforms.

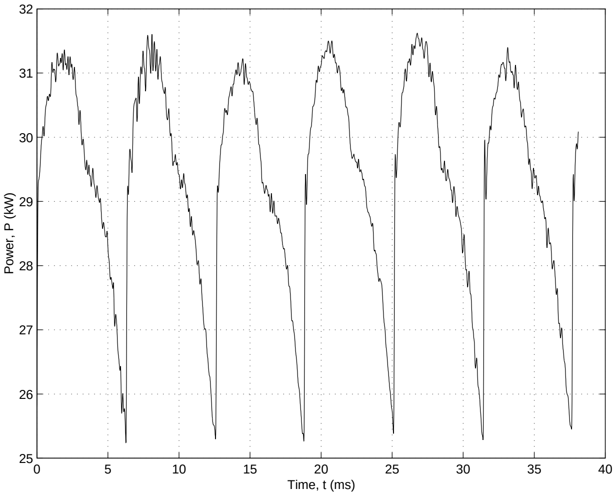

Fig. 10. Power fed by the generator.

4 MECHANICAL VIEW

Mechanical testing focused on controlling the axial forces between rotor and stator. A slightest deviation of the stator from the center point causes strong attractive force in the direction of deviation. It was found necessary to use support bearings at the outer radius of the rotor to ensure a correct position of the rotor. Obviously in the further studies one goal should be a construction in which the need of support bearings may be eliminated. This means a support structure which is rigid enough and shaft bearings which are free of clearances.

Due to the large axial forces the assembly of the rotor with magnets in place is very difficult. However, the design of the prototype enables the placing of magnets one by one with the rotor already in correct position, which proved to be a successful method.

5 CONCLUSIONS

To the authors’ best knowledge this is one of the largest prototype generators of this configuration. The overall electromagnetic performance of the generator is good and is in a nice agreement with the computed performance. A few goals for further study has arisen during these preliminary tests. The symmetry of all the phase voltages may not be easily achieved and consequently the use of several diode bridges for this type of winding connection should be considered. That would eliminate circular currents and power fluctuations. Special attention should also be paid to mechanical design in order to reliably control the strong axial forces.

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